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Factors Controlling Soil Strength, Soil Physical Disturbance, Seedling Recruitment, and Recovery After Clearcut Logging of Lodgepole Pine on two contrasting soil types of Northern Colorado

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FACTORS CONTROLLING SOIL STRENGTH, SOIL PHYSICAL DISTURBANCE, SEEDLING RECRUITMENT, AND RECOVERY AFTER CLEARCUT LOGGING OF LODGEPOLE PINE ON TWO CONTRASTING SOIL TYPES OF NORTHERN COLORADO

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ABSTRACT, from Jonas Feinstein's MS thesis:

FACTORS CONTROLLING SOIL STRENGTH, SOIL PHYSICAL DISTURBANCE, SEEDLING RECRUITMENT, AND RECOVERY AFTER CLEARCUT LOGGING OF LODGEPOLE PINE ON TWO CONTRASTING SOIL TYPES OF NORTHERN COLORADO

Soil strength is a critical measurement for understanding root interactions within a soil matrix. This measurement is complicated by factors affecting soil strength such as porosity, soil moisture content, bulk density, and coarse fraction within the soil matrix. I conducted a paired sampling design between soil strength estimates paired to soil bulk density with associated soil moisture and coarse fraction values in low, high and control disturbance categories resulting from clearcut harvesting methods in similar soil textures derived from different parent material in a predominantly lodgepole pine (Pinus contorta, var *latifolia*) forest type. In both soil types I found that bulk density was not a suitable replacement for bulk density. In both soil types a negative relationship was observed, where granite derived soils show a steeper slope than fine textured soils. I found that soil strength of sandstone derived forest soils was driven by soil moisture with high bulk density and high moisture values, and low strength estimates in clearcuts, while uncut controls had lower bulk density and low moisture values, and higher strength estimates. Conversely, I found the granite derived soil strength to be driven by the amount of coarse fraction present in the

soil matrix. Porosity did not drive soil strength; water and coarse fraction content were the overriding covariate in determining soil strength and masking any effect of porosity. I used this understanding of the intimate relationship between soil moisture and coarse fraction on soil strength on the same two contrasting parent material to determine suitability of soil strength as a proxy for soil compaction in five disturbance categories resulting from mechanical harvesting in clearcuts in eleven granite derived sites and three sandstone derived sites. Clearcut areas both granite and sandstone derived soils showed clearcuts had significantly lower soil strength estimates compared to uncut control stands. We also found that soil strength in recent clearcuts in both soil types was significantly lower than in stands that were cut 10-20 years ago and uncut control stands. Recruitment of seedlings was sufficient to achieve full stocking levels for the region in both soils. Forbs and grass cover indicated site conditions that are indicative of soil moisture conditions, with graminoids predominately found in dry granite derived sites, and forbs found in mesic sandstone derived sites. Our findings indicate that current best management practices (BMP's) and harvesting techniques in lodgepole pine in the research sites are adequate and look to cause no deleterious effects resulting from soil compaction on seedling recruitment.

Introduction

The proportion of pore space in forest soils influences the ability of tree roots to penetrate soil, obtain water and nutrients, and obtain oxygen for respiration. Forest harvesting with large machinery can compact soils, reducing pore space (McNabb et al.2001) and increasing the resistance of soils (soil strength) to root penetration (Greacan and Sands 1980, Miller et al. 2004, Curran et al. 2005). The degree of soil compaction influences long-term soil productivity (Rab 2004, Ares et al. 2005, Page-Dumroese et al. 2006.), as well as seedling recruitment and growth (Page-Dumroese et al. 1998., Blouin et al. 2005, Flemming et al. 2006).

Studies have assessed soil strength and bulk density to understand soil compaction and the overall effects of soil compaction on biotic communities (Miller et al. 2001, Miller et al. 2004). Across a spectrum of soil textural classes and moisture regimes, root growth and elongation are severely impacted as soil strength approaches 2000 kPa in sandy soils, or 4000 kPa in clayey soils (Miller et al. 2001). The combinations of spatial variation in soil texture and variable impacts of machine traffic generate high variation in soil strength, requiring a site specific approach for determining harvesting impacts (Page-Dumroese et al 2006).

I developed a study to determine the impacts of harvesting of lodgepole pine stands on soil compaction and vegetation response to compaction. The objectives of this research were to:

(1) understand how bulk density, porosity, soil moisture, and coarse fraction influence soil strength in a spectrum of disturbance categories in similar soil textures of contrasting parent material;

(2) determine variations in soil compaction and vegetation responses within harvesting units; and

(3) determine the rate of recovery from any soil compaction that might develop from a harvesting operation.

Materials and Methods

2.1 Site Description

The study sites are located in three areas of the Roosevelt National Forest of Northern Larimer County, in the Northern Front Range of Colorado approximately 100 km W NW of Fort Collins. The forests were dominated by lodgepole pine (*Pinus contorta*, var *latifolia* (Engelm.) Critchfield), with lesser amounts of spruce (*Picea. engelmannii* Parry *ex* Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and limber pine (*Pinus flexilis* James). Forest management in the area typically includes clearcut harvesting on century (or longer) rotations, followed by natural regeneration. Typical environmental factors for this area include a mean annual precipitation from 510 – 1020 mm,

mean annual temperature from 2–4 °C, elevation from 2680 to 2870 m, and 0 to 5° slopes.

Two types of parent material lead to two major types of soils in the area. Granite derived soils described as a very stony loamy clay belong to the Granile - Catamount families (very stony; loamy-skeletal, mixed nonacid, shallow Typic Cryorthents). This soil comprises the majority of local landscape. Soils developed in sandstone/shale parent materials have a similar texture and are described as loamy clay within the Granile - Herd families (fine, montmorillonitic Mollic Cryoboralfs).

Both soils exhibited similar diagnostic features in terms of similar textures and depth of soil horizons (Figure 1 & 2). The primary difference in soil taxonomy between the two soils was the presence of many stones in the granite derived soil, and a high content of water in the sandstone derived soils. The sandstone derived soils had blue and grey mottling or gleying in the lower horizons suggesting water logged/ or anoxic conditions.

2.2 Experimental design

I examined soil compaction in 14 sites, each with a harvested unit paired with an adjacent control stand. Eleven sites were on granite derived soils, nested in two general areas about 40 km apart (Bear Gulch (UTM zone 13 E443975 N4524676, NAD27, and Roach, UTM zone 13 E403739 N4536449 (NAD27). The other three sites were on sandstone derived soils in the Bull

Mountain area (UTM zone 13 428535E 4531622N, NAD27). Harvest units ranged from 1 to 12 ha.

All harvesting treatments used the same prescription and employed best management practices (BMP's) with respects to adjacent streams and riparian areas. Harvests were conducted in winter using tracked equipment for felling and large rubber tired machinery for skidding; the amount of snow cover was not measured, but likely ranged from 20 to 50 cm. Logging slash was piled and burned on the 11 granite derived sites, but no slash treatments were applied on the sandstone derived sites.

I characterized harvesting impacts on soil compaction by measuring soil strength, as this parameter most directly affects plant success (Miller et al. 2004). I ran transects across the slope in each harvested unit (in summer 2005 and 2006). Transects in Bear Gulch and Bull Mountain harvest units had four, 60-m transects (except where the width of the unit was less than 60 m). At Roach harvest units, single transects of 200 m through harvested units were paired with 200 m transects in adjacent, unharvested stands. Soil strength was measured every 0.5 m along each transect in the four-transect sites, and every two meters in the single 200-m transect sites. Strength measurements were taken within a 10-cm radius of the sample point, and points that fell on large rocks, stumps, and logs were not sampled.

Soil strength estimates were collected using a Rimik™ cone penetrometer (Agridry RIMIK corporation, Toowoomba, Australia). Soil strength is estimated

as a cone index (soil strength) of sheer strength using a 30°, 31mm diameter cone to estimate resistance. Strength measurements were assessed with an automatic data logger estimating strength in 1.5 cm intervals up to at least a 15cm depth. Data collection was started when the cone was fully submerged in the O-horizon.

I used a 2 m wide belt along each transect to estimate total percent ground cover of forbs and graminoids, total recruitment of seedlings, and presence/absence of organic soil horizon in each treatment unit.

I identified and estimated fine scale disturbance classes for comparing average soil strength estimates for the top ten centimeters. I used a qualitative post harvest assessment to identify these fine scale disturbance classes: this included areas that were characterized as churned, skid trails, moderate disturbance, no disturbance and slash. These five disturbance classes had a minimum mapping unit of 0.5 meters within the transect. Churned areas were identified as areas where the mineral surface horizon was removed to expose subsurface horizons and or the original surface horizon was covered with a surface of new soil from adjacent pedons. Skid trails were characterized from either rutting or flattened stumps where repeated traffic was evident. Moderate disturbance classes were identified as areas where there likely was mechanical traffic, but were not evident upon visual inspection. No disturbance class was

identified as areas where there was no disturbance or likely disturbance, these included areas around leave trees, snags, and harvest unit edges. Slash classes were identified as slash greater than six inches in depth above the surface horizon.

Soil compaction is sometimes characterized by changes in bulk density rather than soil strength, and these two parameters tend to correlate well (Miller 2004). For comparative purposes, I examined the relationship between soil strength and bulk density across a range of control and harvested units with varying levels of apparent soil disturbance. This sampling used twenty sample points that could be characterized as low and high disturbance in clearcuts, and adjacent control stands. Bulk density samples were collected using a JMC™ backsaver 30 x 1.9 cm bulk density probe (Clements Associates Inc. Newton IA, USA) to a depth of exactly fifteen centimeters in the mineral soil. Samples were stored in water-tight bags, and refrigerated until percent coarse fragment, gravimetric soil moisture, and bulk density could be assessed in the lab using standard lab protocols.

Across two soil types, three locations, and 14 sites, there was a combined 840 samples collected. 180 samples were collected in sandstone derived soils in one site, 180 and 480 samples collected for granite derived soils in two sites.

Only three management units for sandstone derived soils within the Roosevelt National Forest were available for sampling at the time of this study.

The effect of mechanized harvesting was evaluated with a mixed model using proc glimmix (SAS Institute, 2006) to test for differences of soil strength in the average top ten centimeters of the mineral soil horizon between: clearcut and control stands, fine scale disturbance classes within clearcut, between clearcuts and control stands, and times since clearcut. Least Square Means using Tukey's HSD adjusted analysis was used to tell if overall differences in treatment means differed significantly between treatment units and within a spectrum of fine scale disturbance classes in treatment units. Again, sites were identified as the experimental unit in determining degrees of freedom.

The relationships between soil strength and bulk density were examined with simple and multiple linear regressions. To determine the ability to predict soil strength using bulk density, gravimetric soil moisture, and coarse fraction, separate mixed models using proc glimmix (SAS 9.1, SAS institute) were used for each soil type. For the granite derived soil, site was nested in location as a random variable, while sandstone derived soils had site as the sole random variable.

Results

3.1 Paired Sampling Results

Although soil strength and bulk density tend to be positively correlated to reduced root density (Thompson et al. 1987), soil strength in our sampled sites declined with increasing bulk density (mass of fine fraction/soil volume; fig. 3a). The decline in soil strength with increasing bulk density was stronger on the finer textured soils. Upon further inspection of disturbance classes within the granite derived soil type we found no difference ($p=0.06$) between disturbance class and bulk density predicting soil strength (fig. 3b). We did however observe a strong relationship ($p<0.0001$) within sandstone derived soils of disturbance class negatively predicting bulk density (Fig. 3c). Bulk density estimates were consistently low where the majority of the sample consisted more coarse fraction (>2mm particles) than fine fraction in the total core volume (Fig. 7).

Sandstone derived soil control disturbance classes (uncut forested stands) had a two fold increase in soil strength compared to both higher bulk density and lower strength clearcut high and low disturbance classes (Fig. 3c). This pattern resulted primarily from a covarying effect of harvesting on soil moisture (Fig 4a). The effect of soil moisture on sandstone derived soil strengths were further divided into significant disturbance categories within this soil type (Fig 3c). A 10% decrease in soil moisture increased soil strengths in uncut control stands by two-fold. This coincides nicely with the bulk density by soil strength relationship

in sandstone soils. Conversely, there was no significant relationship between granite derived soil moisture and soil strength across disturbance classes (Fig. 4b).

Rock fraction had a much greater influence on soil strength in granite derived soils than in sandstone derived soils in terms of on average increase of soil strengths (Fig 5). Sandstone derived soils showed little variation within sites and between sites, compared to granite derived sites that had a greater variation within sites and between sites. Interestingly, a 50% increase in rock fraction in granite derived soils increased soil strengths beyond the levels that lead to reduced growth of roots. This positive relationship can be further elucidated by the presence of rock fraction influencing bulk density estimates and increasing soil strength in granite derived soils (Fig. 6). This result indicates a decrease in rock fraction as a covarying factor associated with bulk density in predicting soil strength.

Increases in porosity did not significantly result in higher soil strengths for both granite and sandstone derived soils. The regression for sandstone derived soils was not significant (p-value=0.16). Granite derived soils showed a significant regression (p-value=0.01) but the slope of the line was not significant (p-value=0.77) (Fig. 8 a&b).

3.2 Transect Sampling Results

Management units within the three locations showed different proportions of disturbance classes (Figure 12). The Bear Gulch sites had higher area in skid trails (12%) than the Roach sites (3%), but Bear Gulch had lower area of churning (3%) than Roach sites (6%). At the Bull Mountain sites, skid trails covered 8% of the site, with churning accounting for another 20% of the area. In all cases the majority of sample points were characterized as a low disturbance class, with 50%, 63%, and 41% towards Bear Gulch, Roach, and Bull mountain sites respectively. In all sites slash cover constituted very close to 20% of the observed samples.

In all cases, clearcut sites had slightly lower soil strength than adjacent control areas (Tables 3 & 4). Within granite derived soils, clearcut soil strength averaged 1680 kPa, significantly different from 1975 kPa for control units. Clearcut units on sandstone derived soils had strengths of 955 kPa, significantly differed with 1955 kPa for control units. Within clearcut units, skid trails were more compacted (2575 kPa) than areas covered by slash (1730 kPa; Table. 2a & b). In the granite derived soils, skid trails were more compacted than areas of no disturbance, low disturbance, or churning. Clearcut units on sandstone derived soils showed slightly higher strength on areas with no disturbance (960 kPa) than areas with low disturbance (865 kPa).

3.3 Vegetation response

Vegetation cover and seedling recruitment within clearcut units did not relate to soil disturbance classes on granite derived soils (Table 2 a&b). Seedling recruitment did not differ among disturbance classes or soil type. When scaled to per hectare estimates of recruitment, I found that ten year estimates for full stocking for lodgepole pine for the region are met in most sites in granite derived soils. Full stocking levels on sandstone derived soils were not consistently met across disturbance categories (Fig. 13). On sandstone derived soils, disturbance classes differed only in forb cover, declining from 52% with no disturbance to 15-20% in areas with low disturbance, churning, or slash. Skid trails had the lowest amount, with 7% of the area covered with forbs. Forbs appeared to occupy similar average areas across sites within granite (19%) and sandstone (22%) derived soils. Graminoid cover was markedly higher in granite derived soils (45%) compared to sandstone derived soils (5%).

Discussion

The relationship between soil strength and bulk density was largely influenced by factors such as soil moisture and rock content, more so in sandstone derived soils than in granite derived soils. Bulk density was a poor indicator of strength in rocky soils, and only moderately better in sandstone soils. This may be attributed to the high amount (10 to 30% of the total sample

weight) of coarse fragment present in granite derived soils, and a high moisture holding capacity in sandstone derived soils. We determined that the two approaches to assessing soil compaction are not interchangeable. Very rocky soils may be difficult to determine rates of compaction due to limitations in physical soil property measurements such as bulk density and soil strength; but these soils are also likely to withstand machine traffic with little compaction (Miller et al. 2004).

Soil strength and bulk density depend heavily on rock fraction and soil moisture. Bulk density, defined as the mass of fine fraction per unit of soil volume, is low when the volume of soil is occupied by pore space or by rocks, with contrasting effects on soil strength. Soil moisture greatly influenced soil strength in the fine textured soils, and increased soil water content after harvesting led to decreases in soil strength that were not related to any influence from machine traffic. These guiding principles of the influence that the rock fraction and soil moisture present in our study sites, help mold a crucial understanding to a complex soil environment that roots interact with and shape.

Granite derived soils were not responsive to the broader paired sampling disturbance categories; this is a product of two contributing factors: 1) large particles that do not compress into a smaller volume and in the soil environment are not plastic in nature, and 2) many small rocks and clasts present in the soil

matrix inflated soil strength values to reflect a soil environment that shows more rocks than actual compaction. The texture determines how much moisture a soil can hold; as texture increases in sand and rock fraction, a subsequent fall in soil moisture holding capacity is seen (Assouline 2006). Conversely, as fine fraction of soils increases, there is a notable increase in soil moisture holding capacity. This difference in holding capacity is associated with micro pore volume present in the soil matrix (Zou et al. 2001). Soil strength was influenced in granite derived soils by rock fraction. The paradigm of soil moisture as the largest contributor to soil strength holds true, however only with an exception to amount of coarse fraction present in the soil. The role of porosity as a driver of soil strength in these soils was not evident.

With a richer understanding of soil strength to bulk density relationships, we determined that overall, there were significant differences in soil strength between the treatment units of clearcuts and adjacent control stands for both sandstone and granite derived soils. This result however was confounded by the fact that on average, soil strength was higher in uncut control stands for both soils. The increase of soil moisture in fine textured clearcut soils, and subsequent lower soil strength is due to an overall decrease in evapotranspiration and canopy interception of precipitation (Kelliher et al 1992 & 1993), and an increase of decomposition of tree roots from stumps (Page-Dumroese et al 1998).

Seedling establishment is not a concern in coarse soils of our study units; our study's estimates of stocking rates were in excess of target levels for lodgepole pine in the region for 10 years after logging (Alexander & Edminster 1980). Tree establishment rates after logging were generally lower in sandstone derived soils, but this may reflect the more recent time of logging at the sampled sites. On average, the granite derived soils had five years since treatment, compared to sandstone derived soils that had only 2 years since treatment. The fine scale delineation of disturbance classes in both soil types showed that recruitment was highest in churned disturbance class for granite derived soils and low disturbance class in sandstone derived soils. This site level result points to a difference in characterizing soil disturbance and management prescriptions in site specific criteria that has been supported by previous broad scale research (Page-Dumbroese 2006).

Soil strength was significantly higher in uncut versus clearcut areas in both soil types. Upon further inspection, clearcuts in granite derived soils had a somewhat expected gradient of soil strengths across a finer scaled delineation of disturbance classes. Sandstone derived soils were not linked as may be expected to a gradient of disturbance classes. Undisturbed soil classes in both cut and uncut stands of fine textured soil were significantly different with uncut strengths being considerably higher at the .05 level. This may represent a

difference in soil moistures in cut and uncut forests resulting from factors such as canopy interception and sub-canopy evaporation (Kelliher et al 1993). This finding provides us with a better understanding of how important soil moisture is to soil strength and likely expanded root growth across various disturbance classes.

Our last objective was concerned with how soil strength may recover over time since disturbance. With our understanding of moisture influence on soil strength, we were able to understand why soil strengths were significantly lower in clearcuts compared to the mid-age and control stands. Early tree growth in many lodgepole pine systems in this region is regarded as vigorous with single cohorts, producing full crown closure early in the life of the stand. This vigor places demands upon available moisture and nutrient levels within the soil matrix, while simultaneously intercepting precipitation. Recovery time of soils since harvesting was attempted, however, the idea of recovery may be not as important a factor in these soils as previously assumed by the author and as previous research indicates (Miller et al. 2004). The idea that soil strengths would go down to control stand levels as mediated by time. Turns out that soil strength increased with time in both soil types. Clearcuts in both soil types were significantly lower than mid-aged stands and control stands. This may be due to an increase of evapotranspiration and canopy interception of precipitation (Kelliher et al. 1990).

Conclusion

Harvesting did not compact soils on average across units, though some locations within units did show higher soil strength. However, factors such as soil type, parent material, and moisture regime played important roles on what ultimately matter most to trees; whether root growth is achievable at a given time and soil environment. Porosity does not influence soil strength. With a richer understanding of physical soil properties and soil type, recruitment and site productivity may not be a concern with the resistant soil types sampled in this study. Additionally, factors such as long-term soil productivity in these soils may not be as much of a concern to managers compared to other issues mitigated by BMP's, such as stream or habitat quality. Successful recruitment of seedlings remains within stocking levels associated with lodgepole pine forests in the region (Alexander et al. 1980). My research suggests that mechanical harvesting and use of current BMP's are achievable and synchronous goals. This synchrony in management holds true when regarding the long rotations required for wood fiber production and resulting recovery times in the region. My research also suggests that assessment of soil compaction is more fully understood with the use of soil strength estimates.

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Table 1; Individual least square means from mixed model results for soil strength, seedling count, percent forb cover, and percent grass cover by disturbance classes in clearcuts of (a) coarse textured soils and (b) fine textured soils Mean value ± standard error, and least square means significance. Analysis based on critical alpha 0.05, and Tukey's HSD criteria. All disturbance classes with same letter subscript are not significantly different.

(a)

Coarse soils	Soil Strength (kPa) n=11	Seedlings m^2 n=3	% Cover Forbs n=3	% Cover Graminoids n=3
Skid Trail	2574.4 ± 165.9 **a**	0.34 ± 0.02 **a**	18.3 ± 6.14 **a**	48.1 ± 12.6 **a**
Churned	1868.0 ± 189.6 **b c**	0.20 ± 0.03 **a**	18.2 ± 5.22 **a**	33.0 ± 10.7 **a**
Low Disturbance	2175.5 ± 156.4 **b**	0.24 ± 0.01 **a**	23.1 ± 4.21 **a**	49.6 ± 8.58 **a**
No Disturbance	1905.3 ± 244.4 **b c**	0.05 ± 0.001 **a**	17.5 ± 4.90 **a**	52.8 ± 10.0 **a**
Slash	1727.3 ± 166.3 **c**	0.12 ± 0.01 **a**	15.9 ± 4.90 **a**	41.5 ± 10.0 **a**

(b)

Fine soils	Soil Strength (kPa) n=3	Seedlings m^2 n=3	% Cover Forbs n=3	% Cover Graminoids n=3
Skid Trails	947.0 ± 76.4 **a b**	0.12 ± 0.02 **a**	7.07 ± 5.45 **c**	5.06 ± 2.34 **a**
Churned	953.8 ± 152.2 **a b**	0.16 ± 0.03 **a**	17.5 ± 4.90 **b c**	2.60 ± 2.89 **a**
Low Disturbance	867.1 ± 73.2 **b**	0.32 ± 0.03 **a**	19.3 ± 5.30 **b**	7.32 ± 2.21 **a**
No Disturbance	959.1 ± 152.2 **a**	0.17 ± 0.02 **a**	51.7 ± 5.85 **a**	3.94 ± 2.66 **a**
Slash	956.8 ± 90.5 **a b**	0.05 ± 0.01 **a**	14.6 ± 6.13 **b c**	4.93 ± 2.89 **a**

Table 2. Individual least square means from mixed model results for soil strength, seedling count, percent forb cover, and percent grass cover by age since clearcutting in clearcuts of coarse soils. Mean value ± standard error, and least square means significance. Analysis based on critical alpha 0.05, and Tukey's HSD criteria. All ages with same letter subscript are not significantly different.

Coarse soils	Soil Strength (kPa) n=3	Seedlings m^2 n=3	% Cover Forbs n=3	% Cover Graminoids n=3
Control	1974.5 ± 76.8 **a**	0.74 ± 1.01 **b**	23.8 ± 3.82 **a**	9.7 ± 5.95 **c**
15-25 Years	1931.2 ± 58.0 **a**	0.77 ± 0.69 **b**	22.3 ± 2.60 **a**	28.6 ± 4.44 **b**
0-5 Years	1683.6 ± 58.0 **b**	5.26 ± 0.69 **a**	19.7 ± 2.60 **a**	45.6 ± 4.43 **a**

Table 3. Individual least square means from mixed model results for soil strength, seedling count, percent forb cover, and percent grass cover by age since clearcutting in clearcuts of fine soils. Mean value ± standard error, and least square means significance. Analysis based on critical alpha 0.05, and Tukey's HSD criteria. All ages with same letter subscript are not significantly different.

Fine textured soils	Soil Strength (kPa) n=3	Seedlings m^2 n=3	% Cover Forbs n=3	% Cover Graminoids n=3
15-25 Years	2047.7 ± 76.8 **a**	8.04 ± 1.91 **a**	34.6 ± 6.75 **a**	6.90 ± 1.68 **a**
Control	1955.1 ± 58.0 **a**	5.73 ± 2.21 **a**	40.1 ± 7.25 **a**	5.36 ± 1.94 **a**
0-5 Years	953.8 ± 58.0 **b**	3.48 ± 1.33 **a**	17.1 ± 5.95 **b**	4.84 ± 1.17 **a**

Table 4. Individual least square means from mixed model results for soil strength for no disturbance category in clearcut and in uncut control. Mean value ± standard error, and least square means significance. Analysis based on critical alpha 0.05, and Tukey's HSD criteria. Categories with the same letter subscript are not significantly different.

	Coarse Textured Soil Strength (kPa) n=11	Fine Textured Soil Strength (kPa) n=3
No Disturbance (control)	2358.8 ± 126.2 **a**	1951.0 ± 69.0 **a**
No Disturbance (clearcut)	2098.9 ± 153.8 **b**	940.5 ± 66.0 **b**

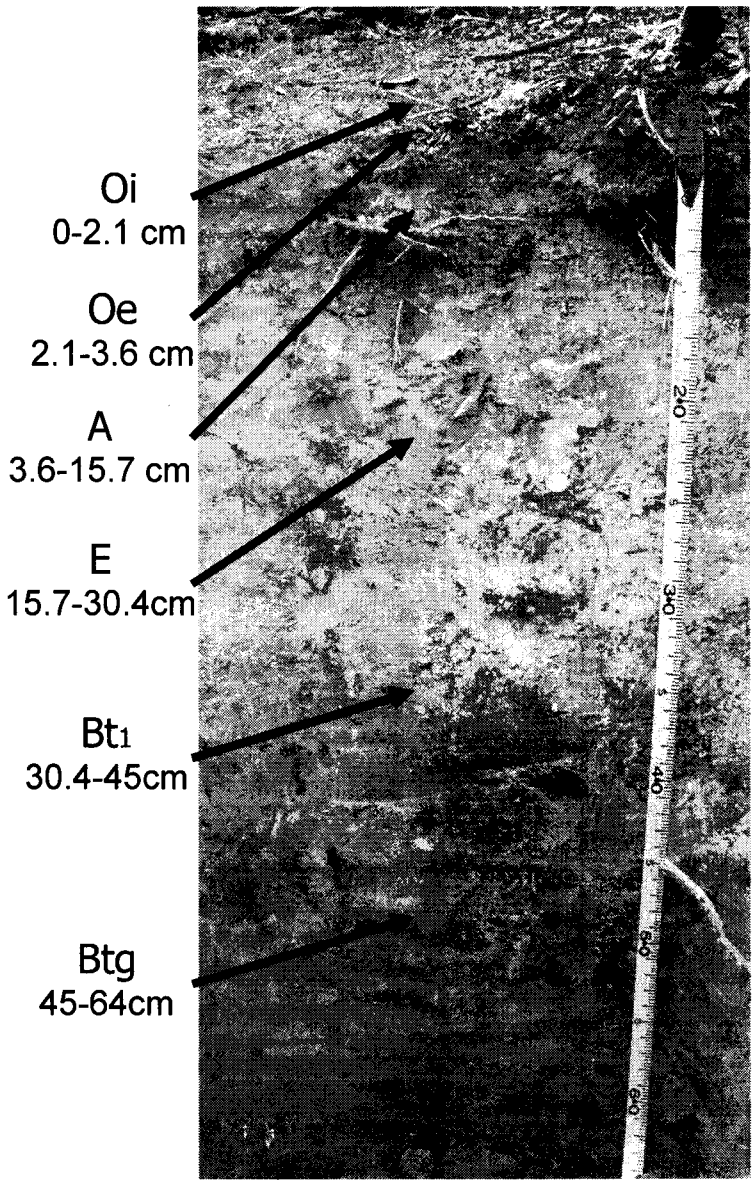


Fig. 1; Typical sandstone derived soil profile.

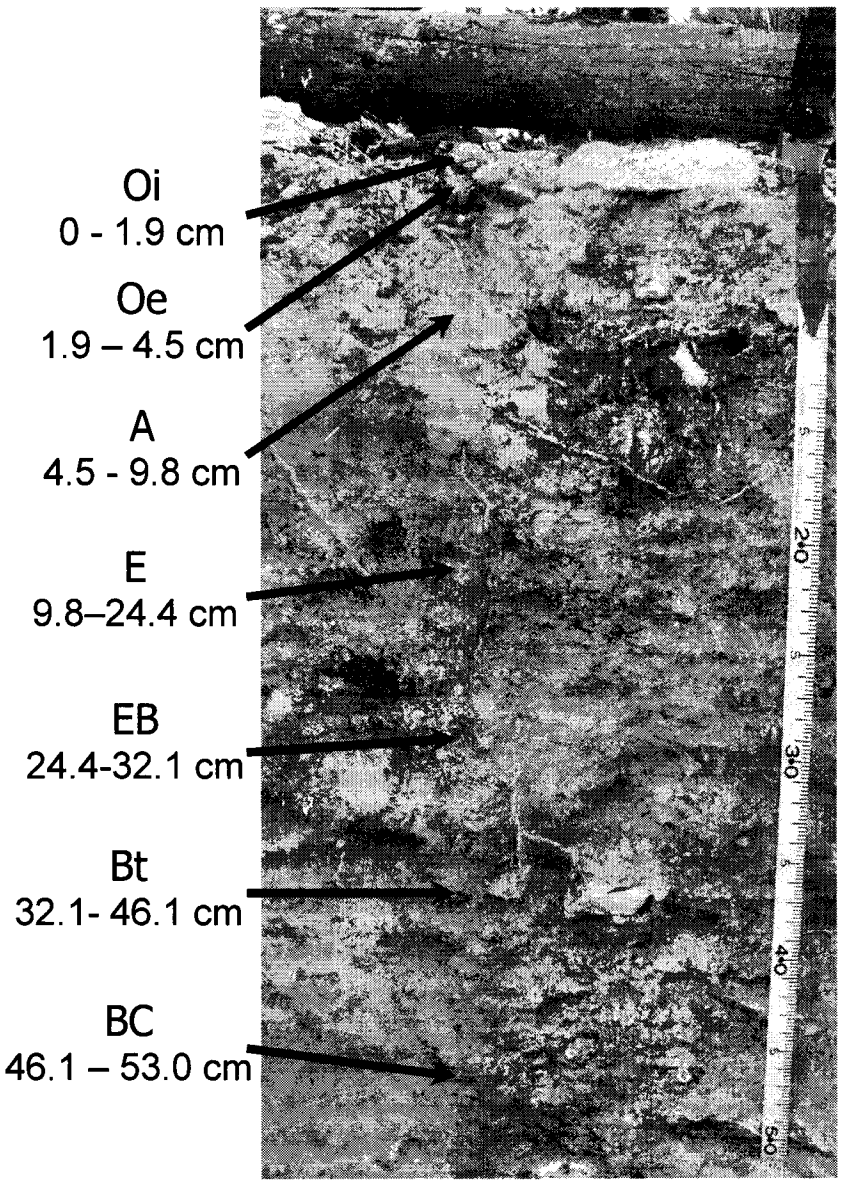


Fig. 2; Typical Granite derived soil profile.

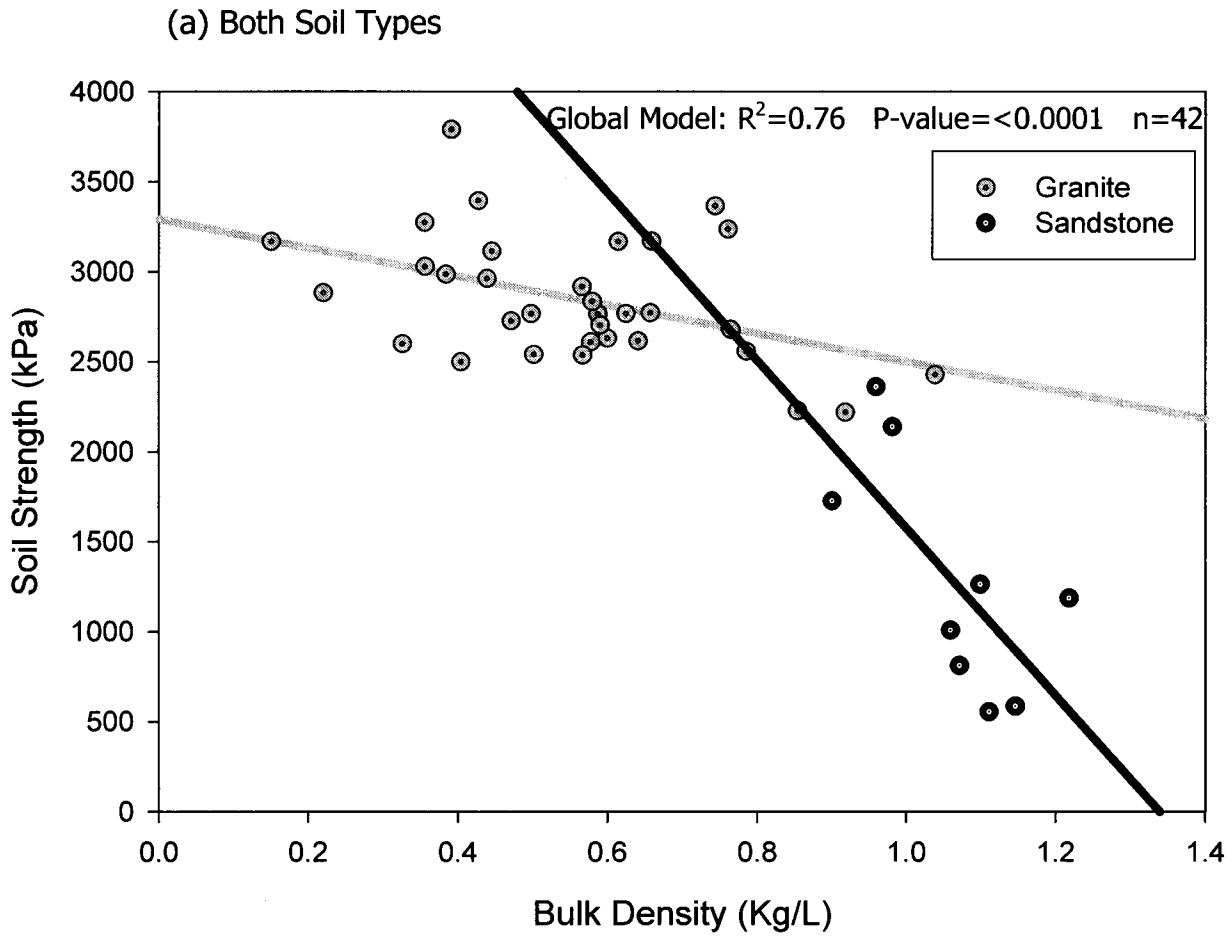
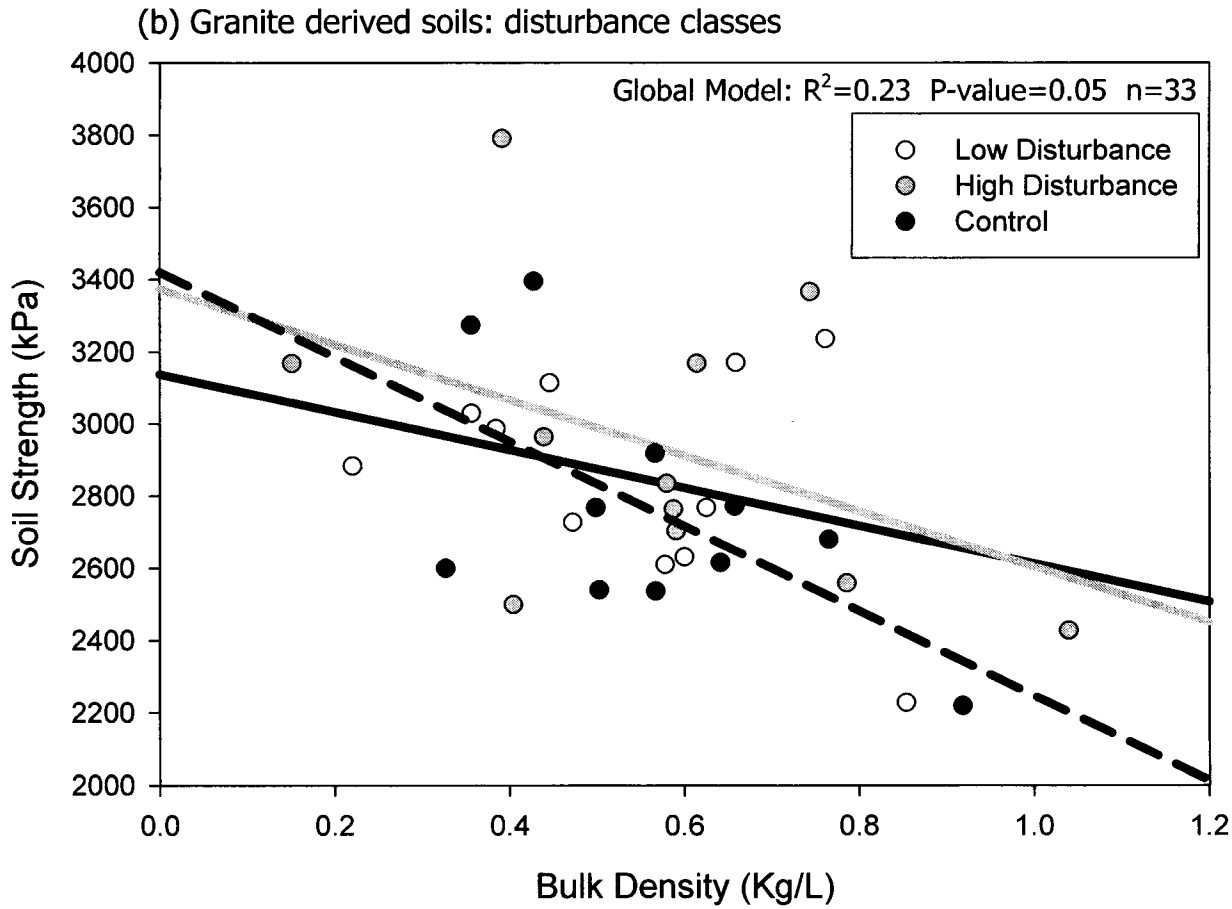
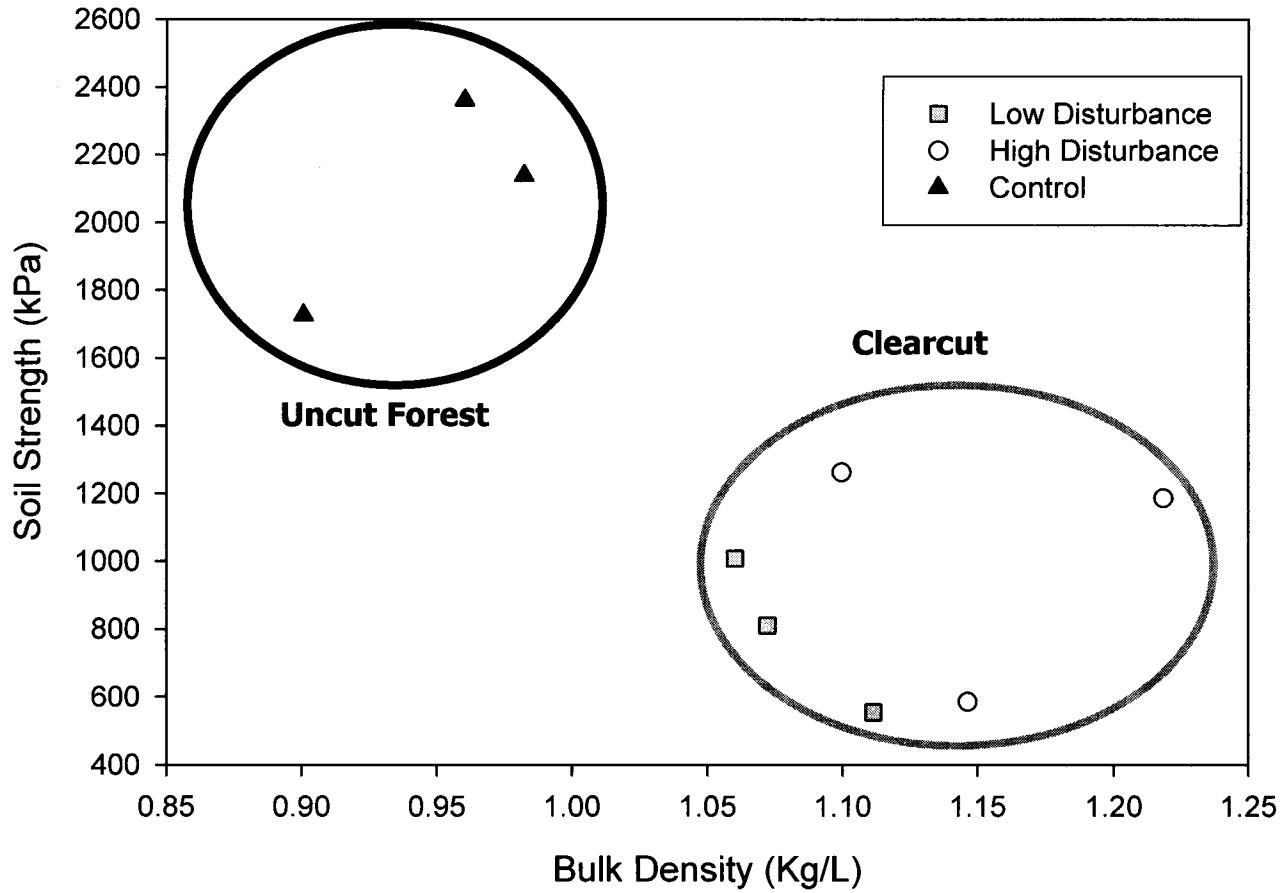


Fig. 3; Mean soil bulk density predicting soil strength of (a) sandstone derived treatments; three treatments in three sites, and granite derived sites three treatments in eleven sites, (b) treatments across granite derived sites only, (c) and treatments across sandstone derived soils.


(b) Granite derived soils: disturbance classes
Global Model: R^2=0.23 P-value=0.05 n=33
Low Disturbance
High Disturbance
Control
Soil Strength (kPa)
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Bulk Density (Kg/L)

(c) Sandstone derived soils: disturbance classes



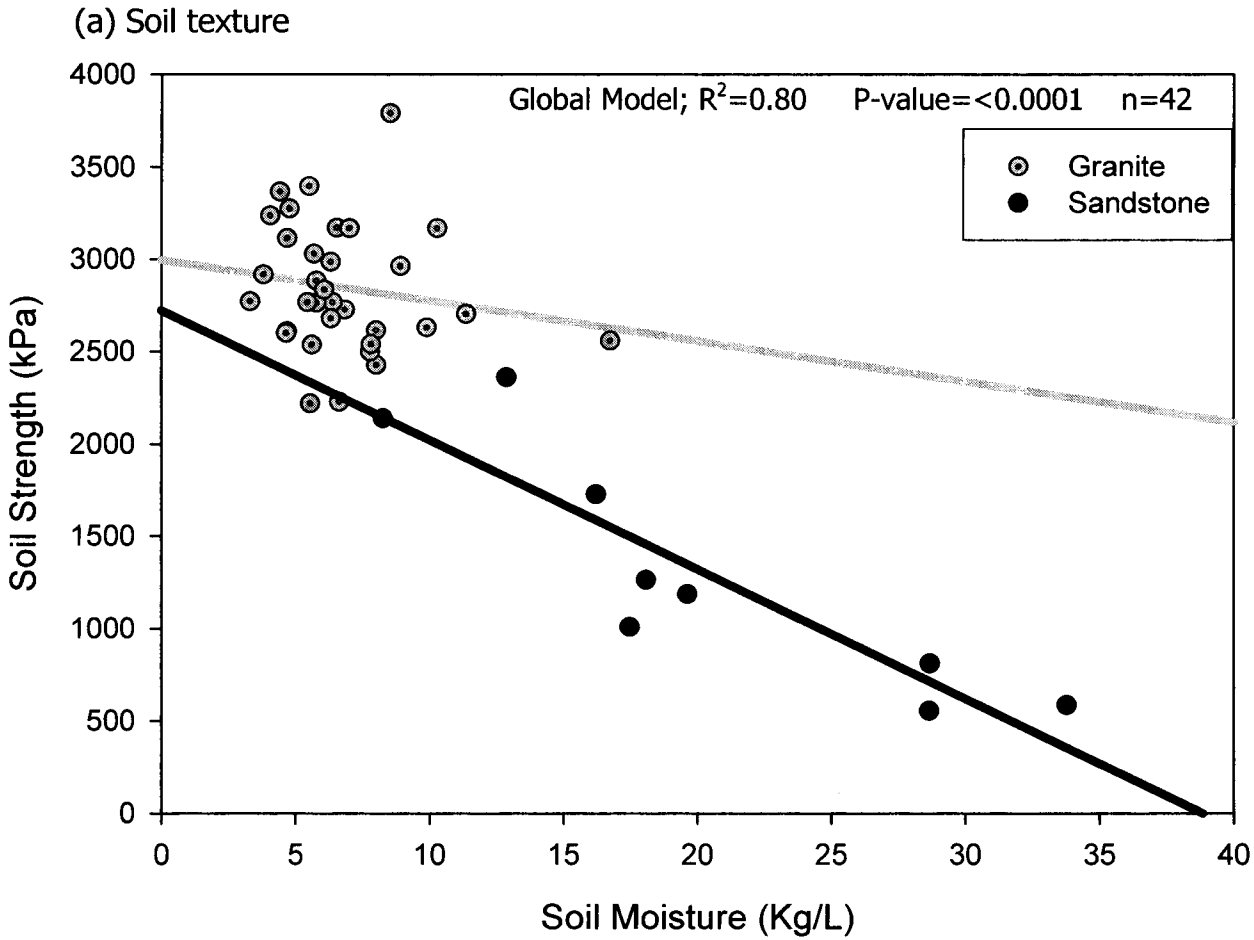
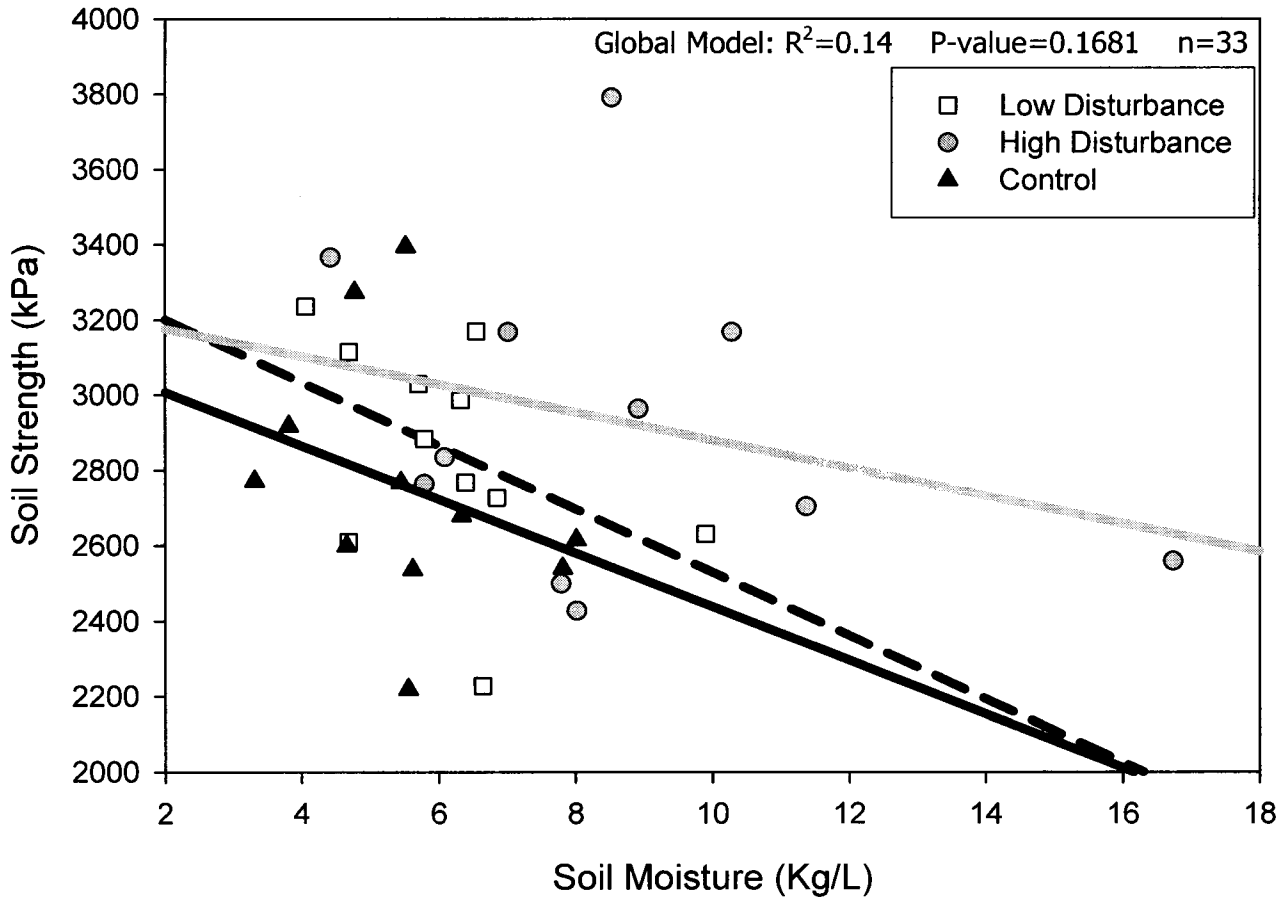
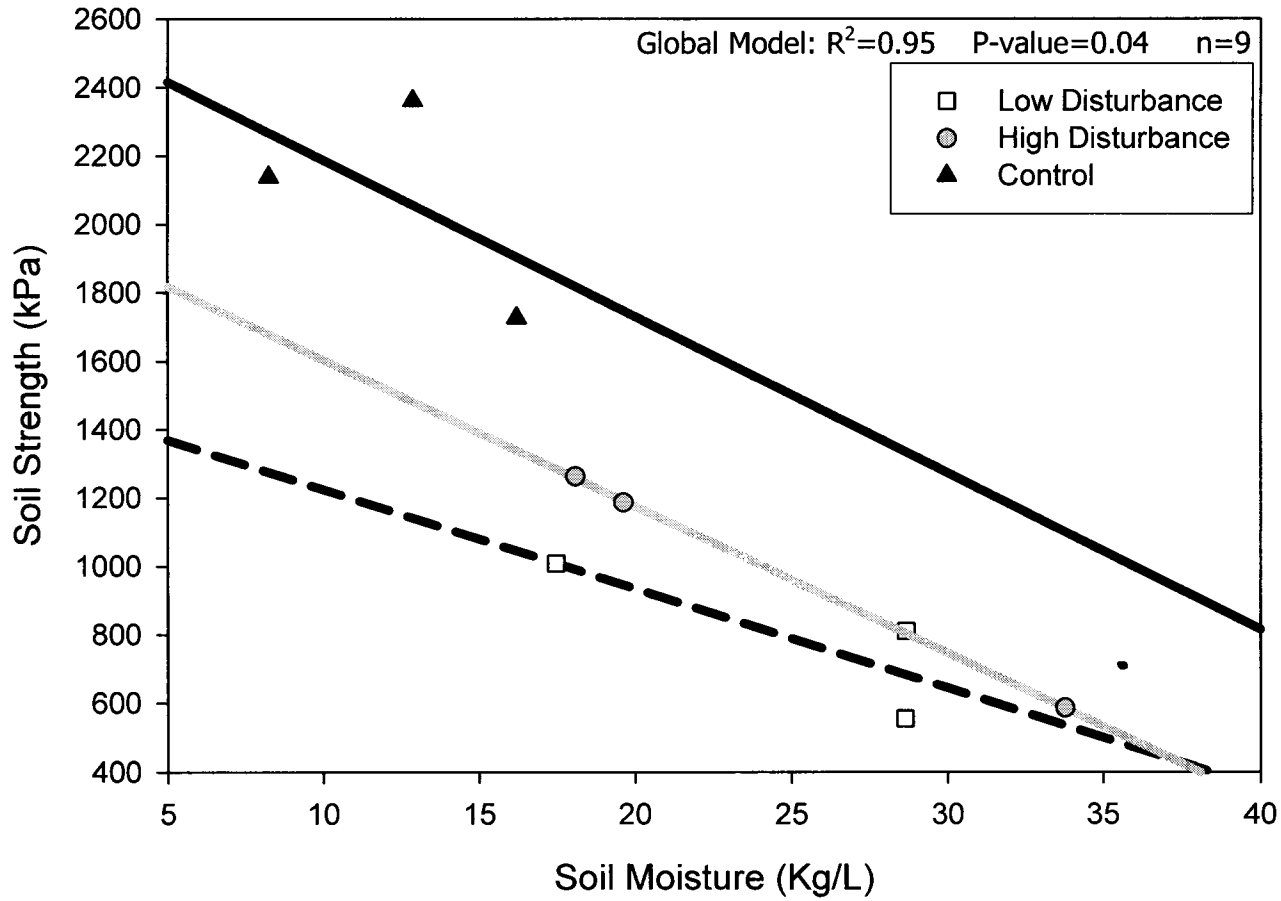


Fig. 4; Mean soil moisture (Kg/L) predicting mean soil strength (kPa) of (a) sandstone derived treatments; three treatments per three sites. Granite derived sites three treatments per eleven sites, (b) treatments across granite derived soils, (c) and treatments across sandstone derived soils.

(b) Granite derived soil; disturbance classes



(c) Fine texture disturbance classes



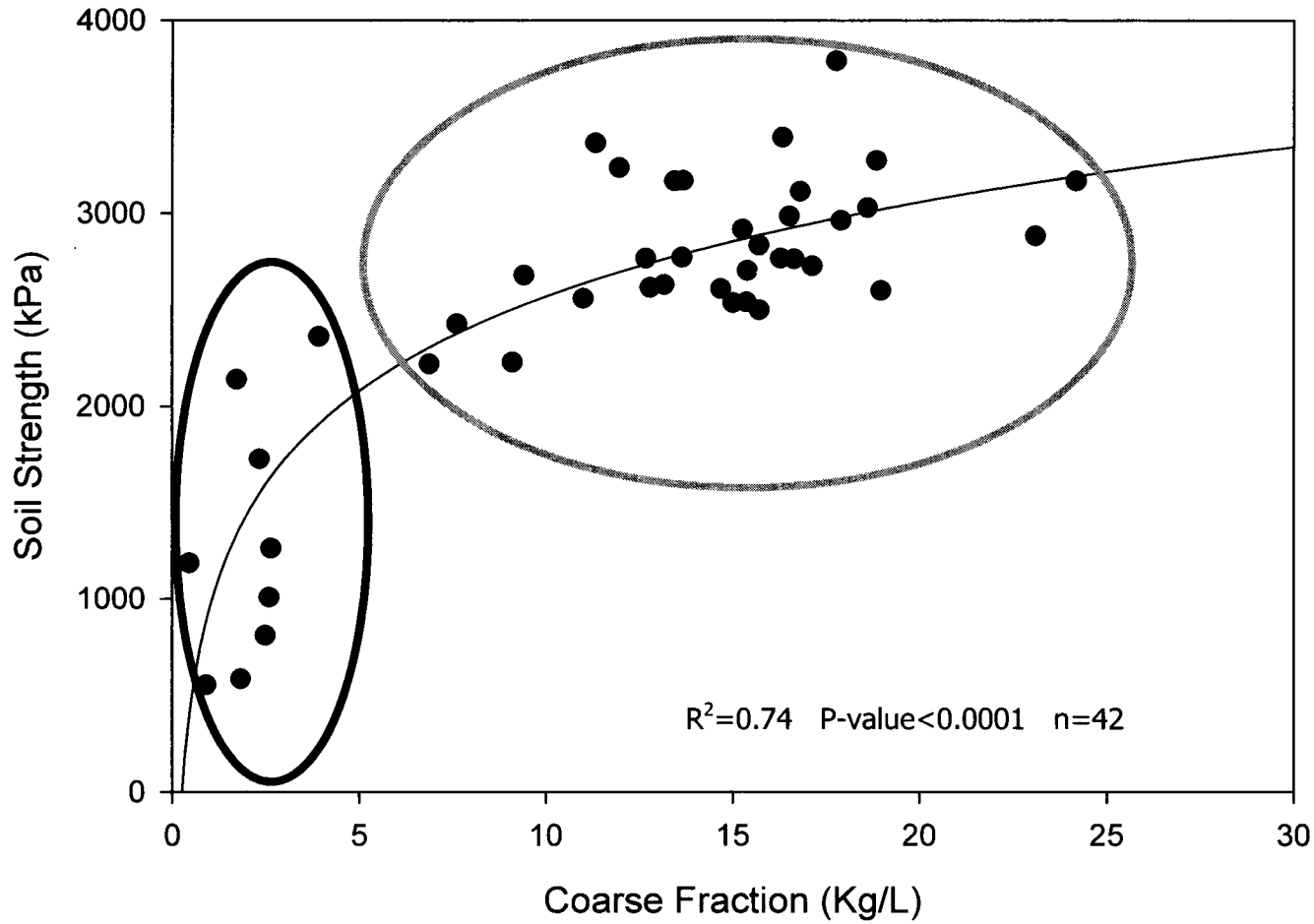


Fig. 5; Mean coarse fraction relationship to mean soil strength in granite (grey circle) and sandstone (black circle) derived soils.

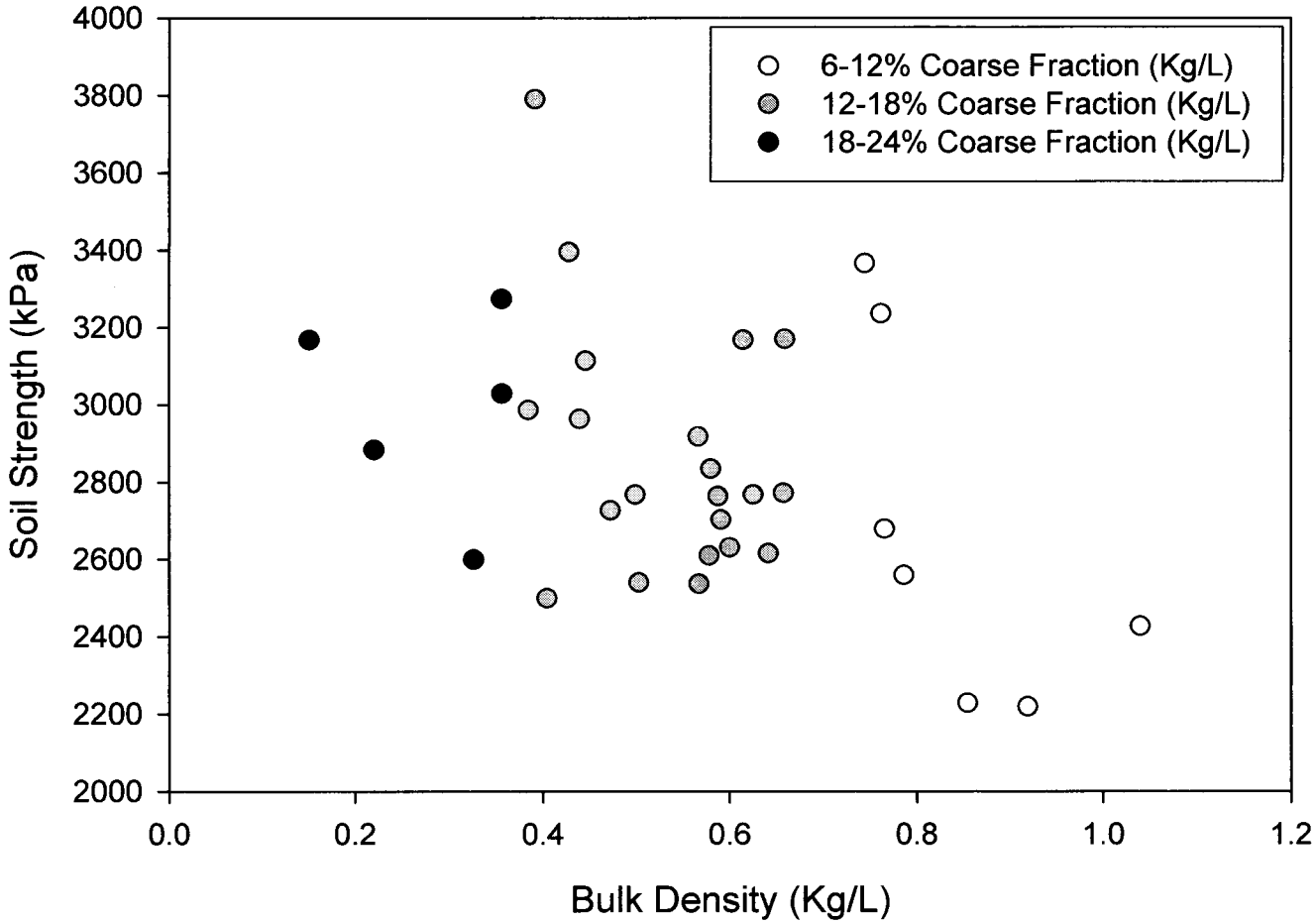


Fig. 6; Mean bulk density relationship to mean soil strength in granite derived soils with coarse fraction mass proportions of total mass balance of soil core.

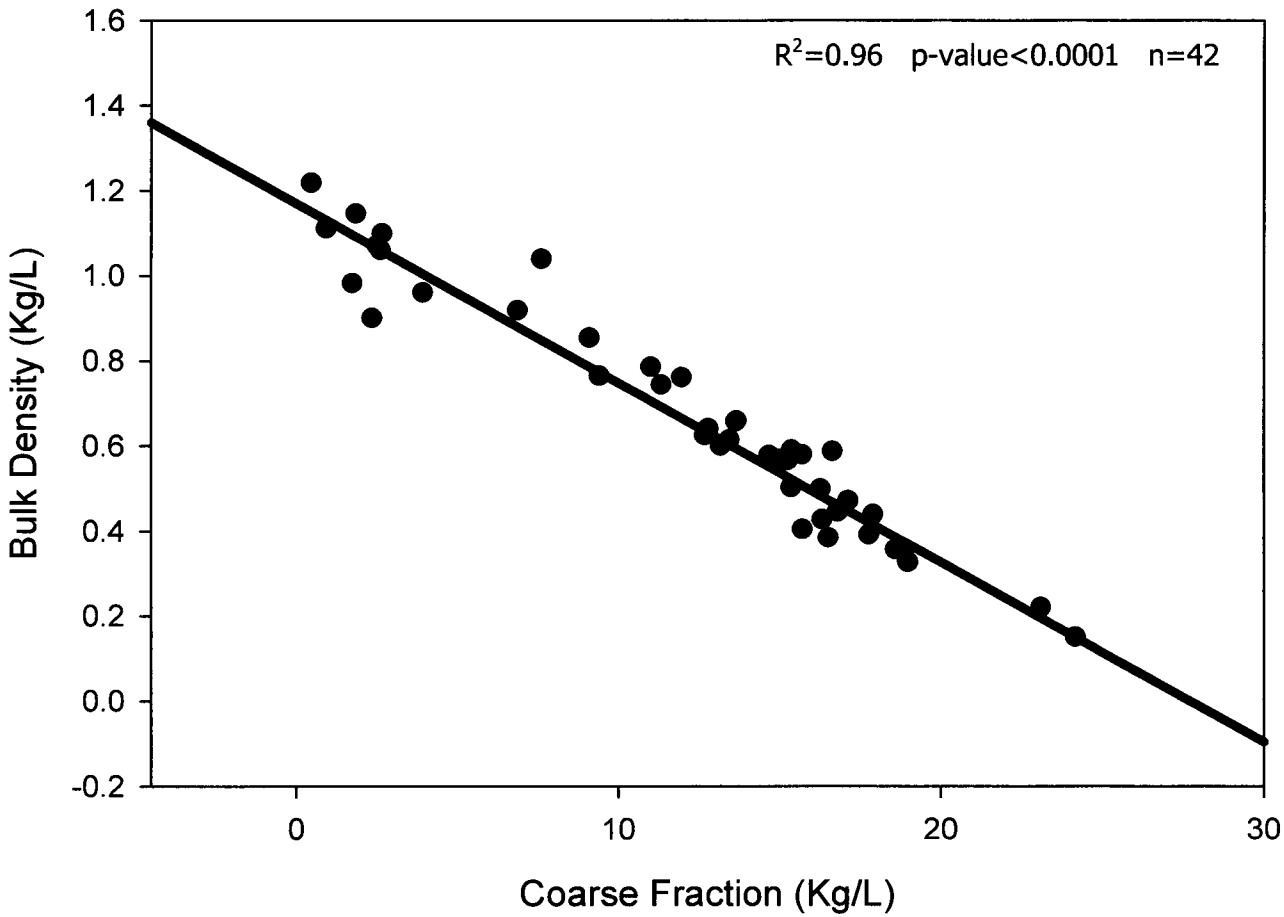


Fig. 7; Mean soil bulk density relationship to mean coarse fraction of total mass balance for both granite and sandstone derived soils.

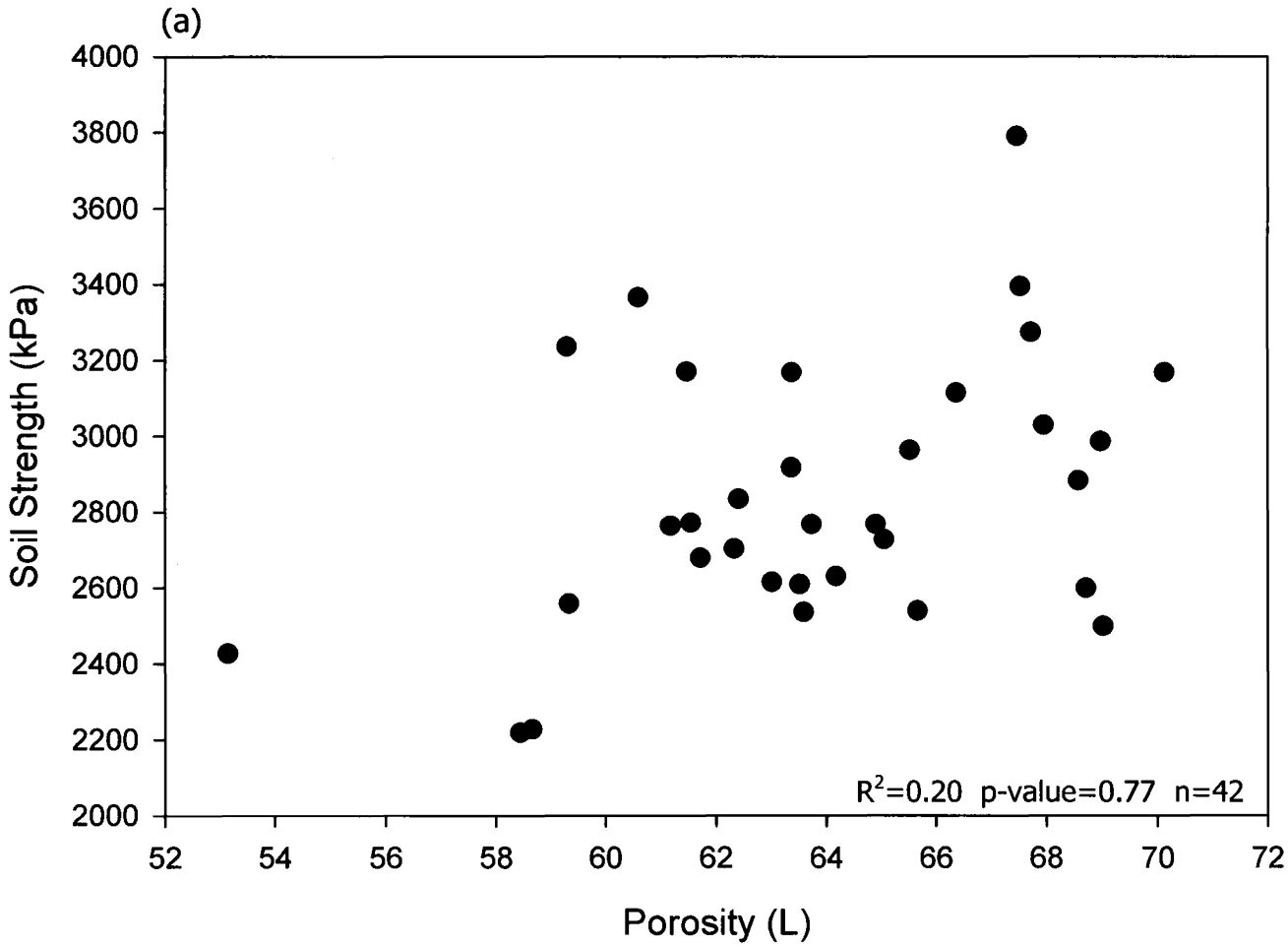
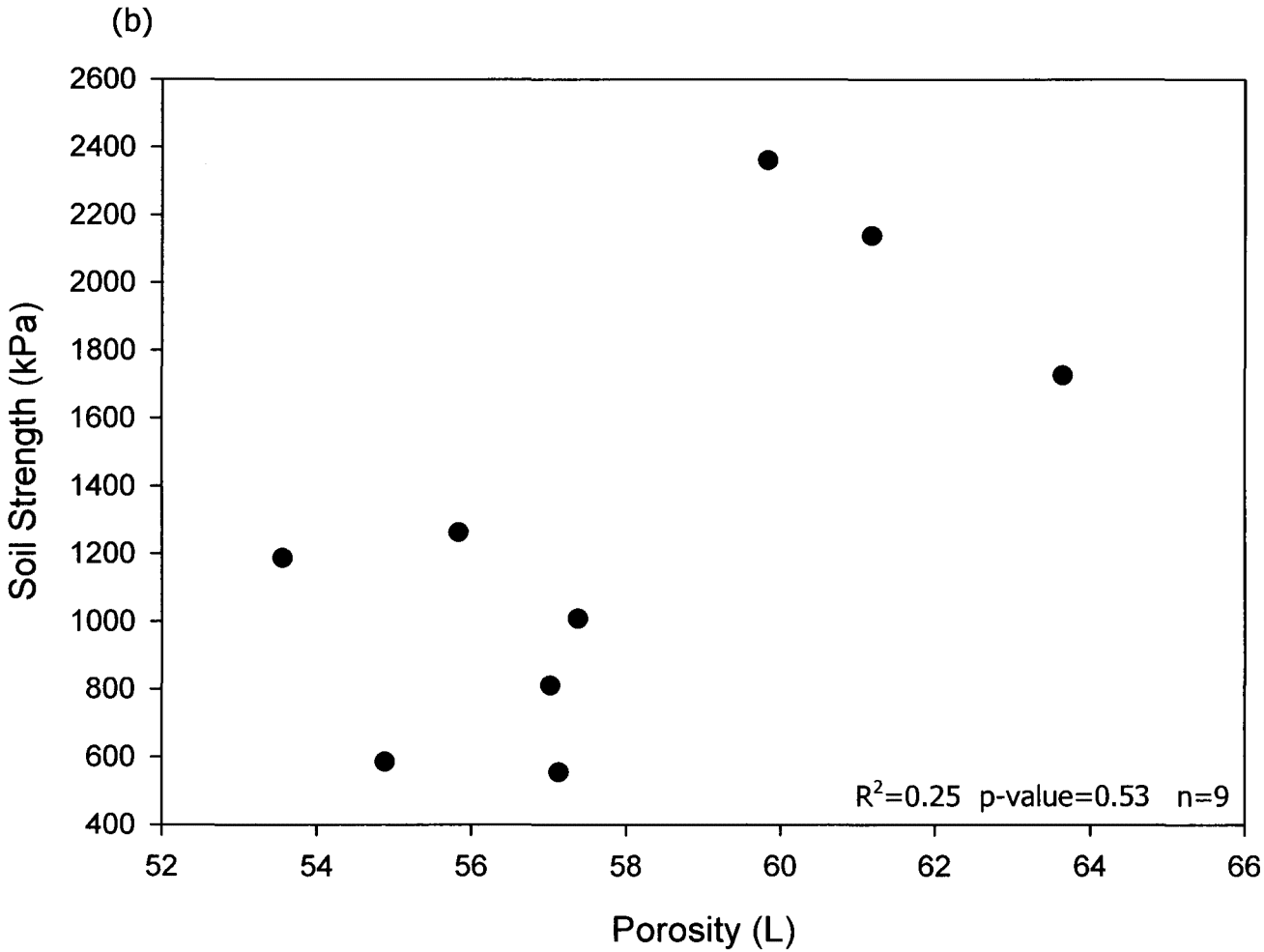


Fig. 8; Mean porosity relationship to mean soil strength in granite (a) and sandstone (b) derived soils.


(b)
Soil Strength (kPa)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
52
54
56
58
60
62
64
66
Porosity (L)
R2=0.25 p-value=0.53 n=9

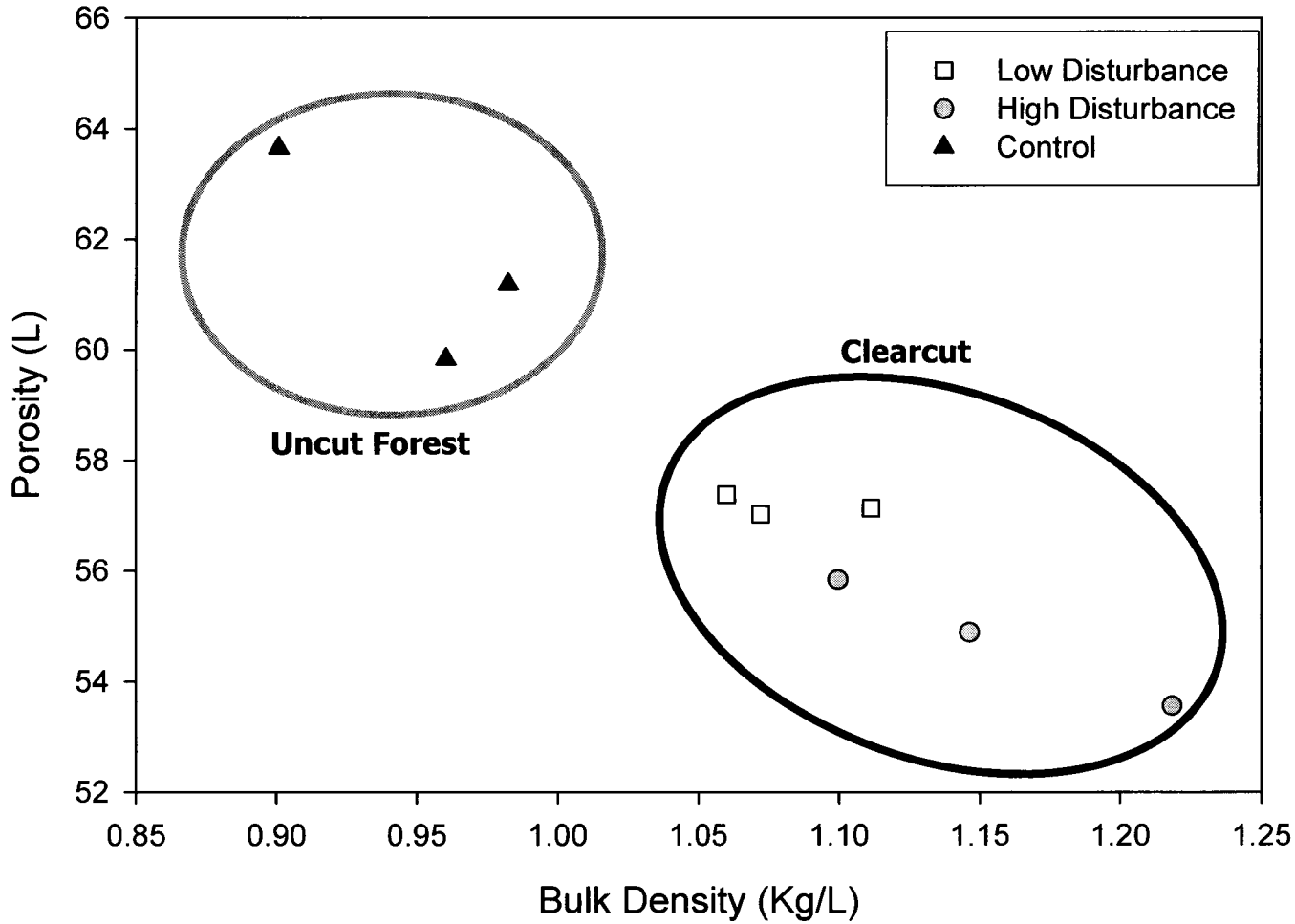


Fig. 9; Mean bulk density relationship to mean porosity across disturbance classes in sandstone derived soils. Grey circle delineates disturbance classes located in uncut forest, black circle delineates disturbance classes in clearcut

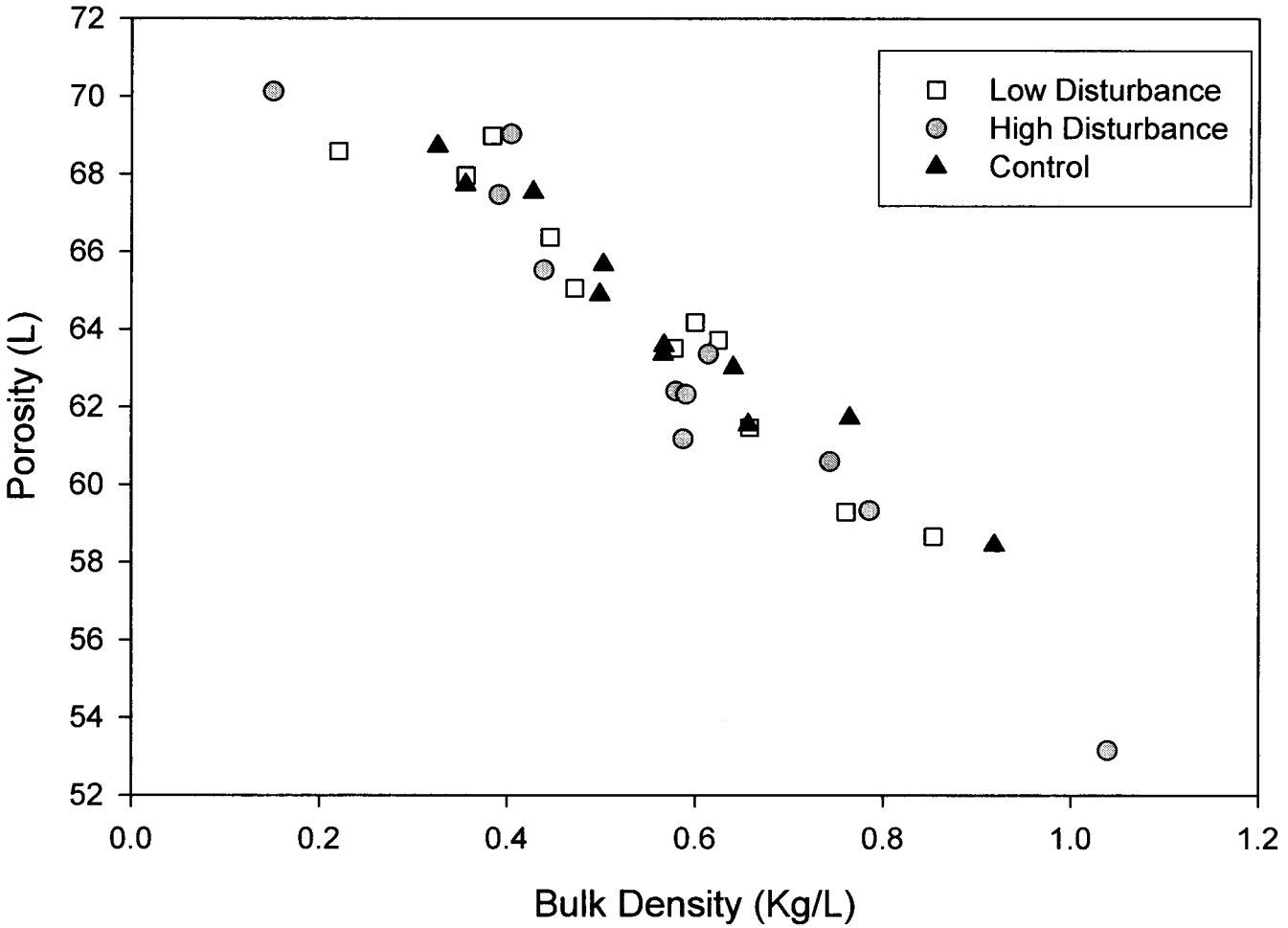


Fig. 10; Mean bulk density relationship to mean porosity across disturbance classes in granite derived soils.

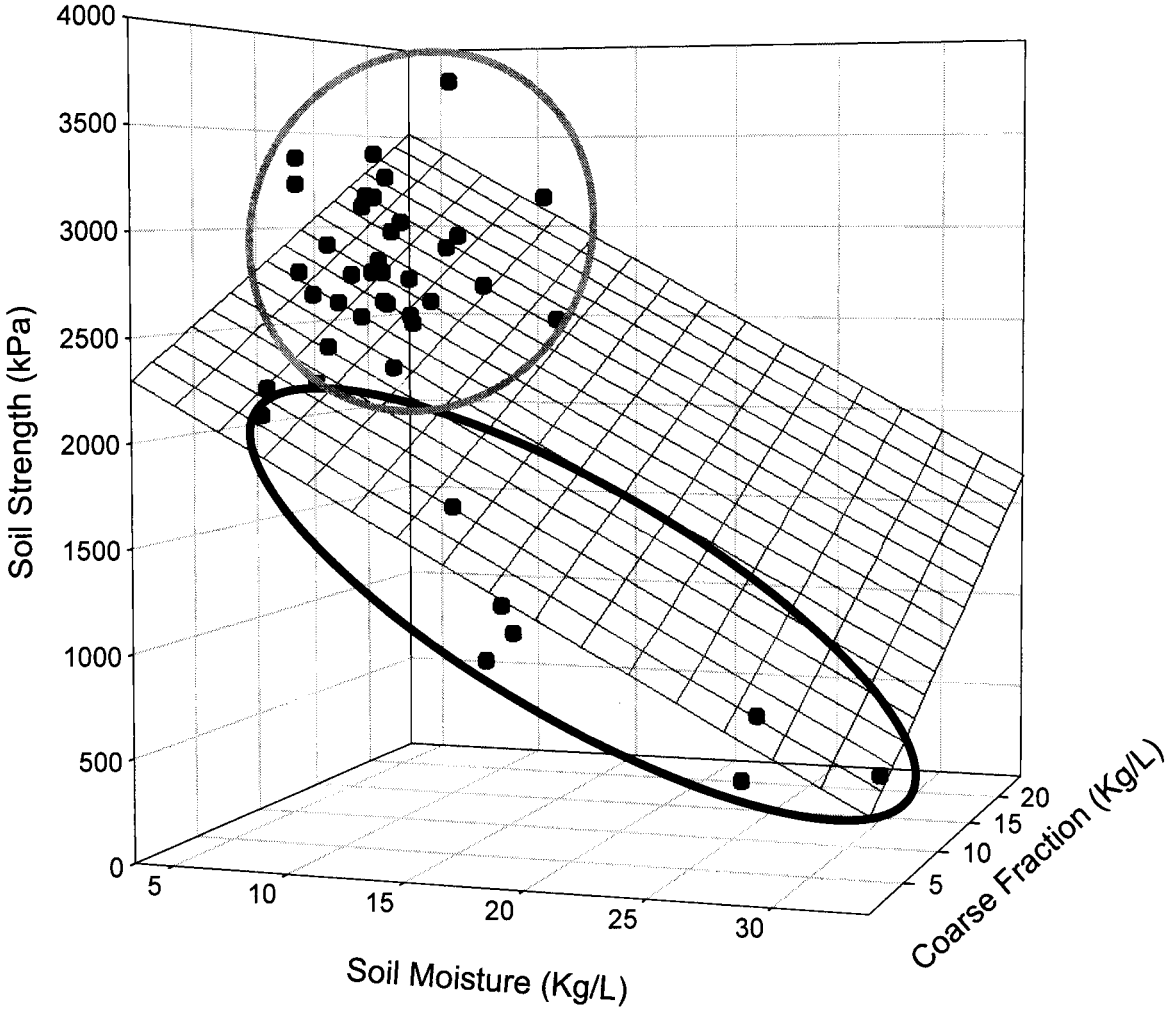


Fig. 11; Granite (grey circle) and sandstone (black circle) derived soils in a linear multiple regression for gravimetric soil moisture and coarse fraction estimates derived from bulk density samples predicting soil strength averages for the top fifteen cm of mineral soil profile.

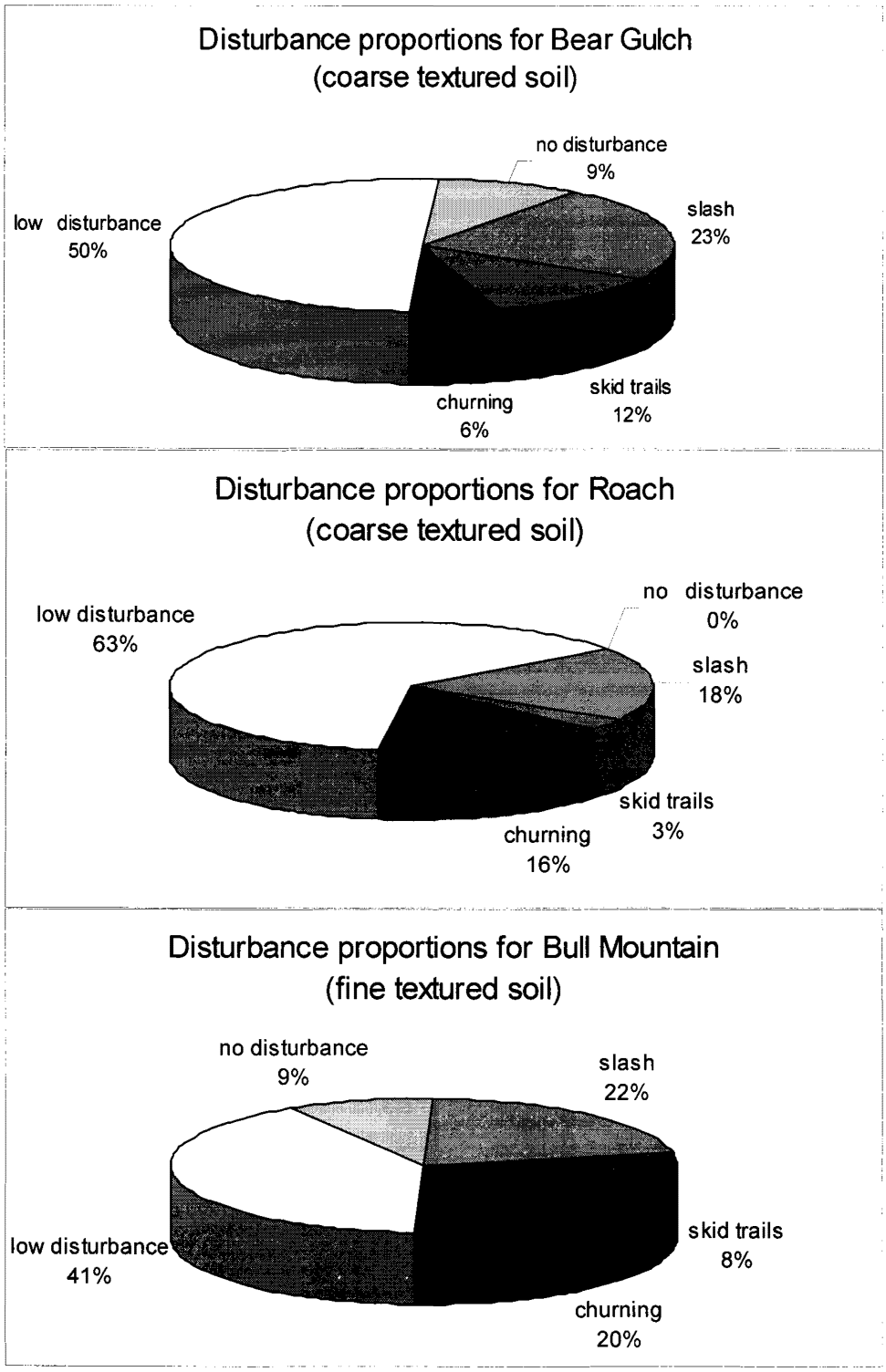


Fig. 12; Sites within both coarse and fine textured soils showing proportion of area sampled within fine scale disturbance classes.

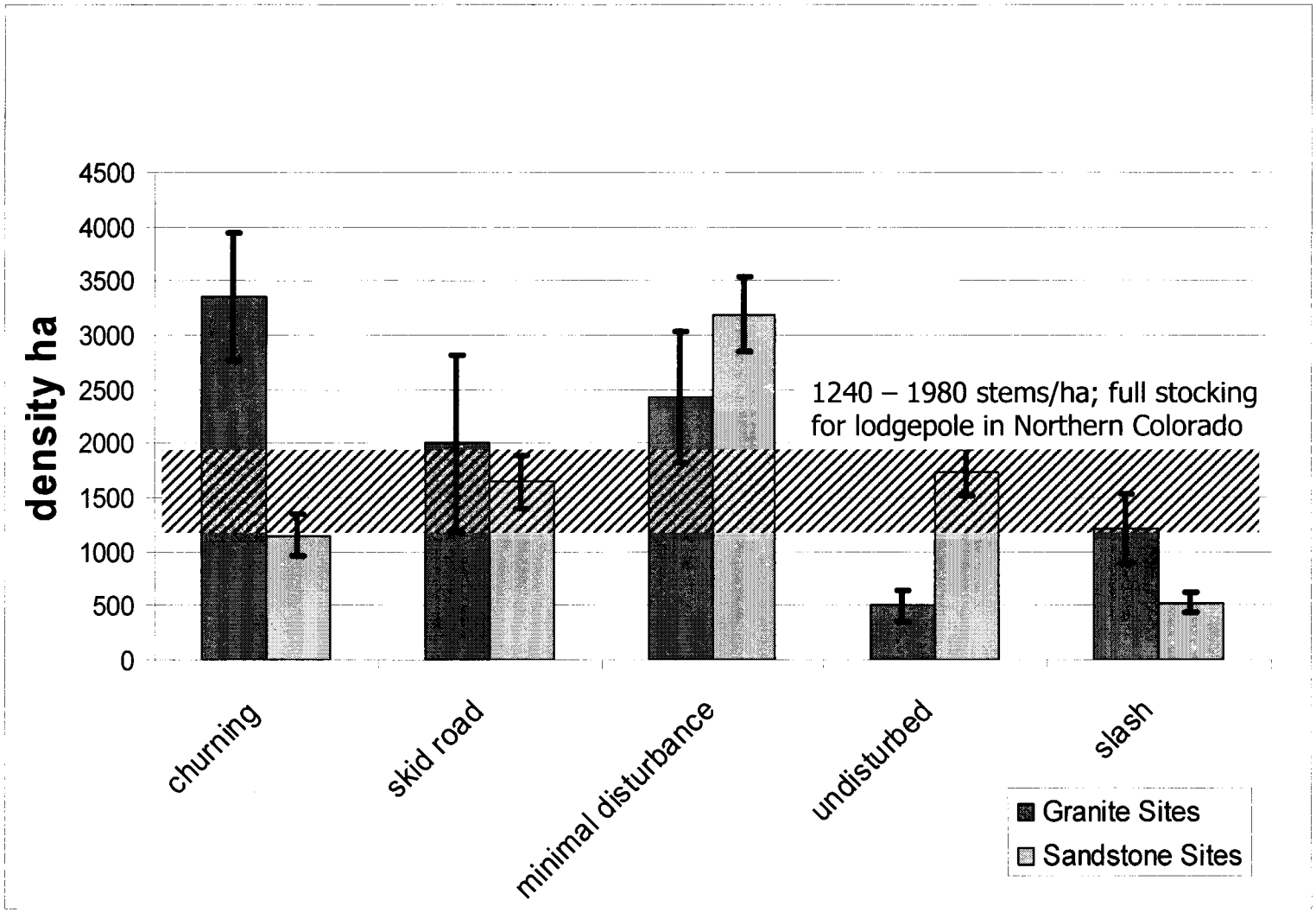


Fig 13; Seedling density per hectare for fine scale disturbance classes in granite and sandstone derived soils. Hatched overlay of expected full stocking levels in Northern Colorado (Alexander et al, 1980).